

# Barrier Buckets in the Fermilab Recycler Ring

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**Abstract.** The Fermilab Recycler Ring is an 8GeV permanent magnet antiproton storage ring. It is equipped with a wide-band rf system to produce barrier buckets of any shape. We report here on some beam dynamics simulation studies and beam experiments carried out using the barrier rf system in the Recycler Ring.

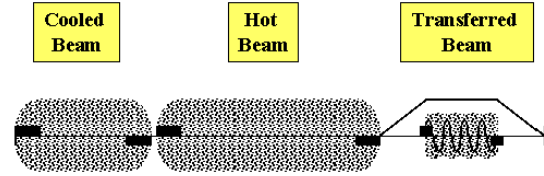
## INTRODUCTION

The Fermilab Recycler Ring (RR) [1] has been built with the goal of increasing ppbar collider luminosity for Run-IIb in the Tevatron from  $5E31\text{cm}^{-2}\text{sec}^{-1}$  to  $2E32\text{cm}^{-2}\text{sec}^{-1}$ . The RR will be the main pbar storage and cooling ring in the Fermilab accelerator complex. Hence, RR plays a vital role in future Tevatron collider operations.

Presently, we are commissioning the RR using protons from the Fermilab Booster or pbars from the Accumulator Ring (AR). The beam transfer in both cases has to be done by separating previously transferred beam from the new transfer. In future, unused pbars at the end of each collider run will be decelerated first in the Tevatron from 1 TeV to 150 GeV and then in the MI from 150 GeV to 8 GeV and, finally, transferred to RR. The emittance of the pbars from the Tevatron at the time of injection to RR is expected to be  $<16\text{ eV-s}$  in longitudinal plane and  $<20\pi\text{-mm-mr}$  in transverse planes. These pbars will have considerably larger emittance as compared to the pbars from AR. In RR, we have to separate the cold pbars and the hot pbars in azimuth. Thus, at any given time it is required that a maximum of three zones in RR azimuthally separated, viz., transfer, stacked (cooled) and hot beam regions as indicated in Figure 1. All these specific needs can be met only by having barrier buckets[2] in the RR and be able to dynamically change their locations in the RR azimuthally.

The barrier bucket rf technology was invented at Fermilab[2] in 1983 and used successfully in the pbar Debuncher Ring. The shape of barrier pulses used in the Debuncher Ring was sinusoidal. In the RR we adopted bipolar square barrier pulses. Recently, a multi-particle beam dynamics 2-D simulation code[3] has been developed to study beam dynamics issues in RR and a comprehensive Hamiltonian formalism of

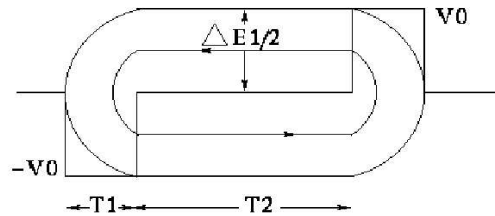
particle motion in barrier rf buckets is presented in reference 4.



**FIGURE 1.** A schematic view of cooled, hot and transfer beam regions in RR separated using barrier buckets. The transfer region has 2.5MHz rf wave with rf bucket matched to the beam coming from MI.

## BARRIER BUCKETS IN RR

A wide-band RF system capable of generating many barrier buckets of any shape has been built[5] and installed in RR. The maximum height of a barrier pulse is set to about  $\pm 2\text{kV}$  each. The width of a pulse can be varied. The pbar beam from AR will be having 2.5MHz rf structure and that from RR to MI can have 2.5MHz or 7.5MHz rf structure. The rf system can produce 2.5MHz/7.5 MHz rf buckets in between barrier buckets. Figure 2 shows a schematic view of a barrier bucket in RR generated using square pulses.



**FIGURE 2.** A schematic view of a barrier bucket in RR. Equal Hamiltonian contours are also shown.

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Half-height of a barrier bucket shown in Fig.2 is given by [1,4],

$$\Delta E_b = \left( \frac{eV_0 T_1 2\beta^2 E_0}{T_0 |\eta|} \right)^{1/2}$$

and, bunch area is given by,

$$\mathcal{A} = 2T_2 \Delta E + \frac{8\pi|\eta|}{3\omega_0 \beta^2 E_0 e V_0} (\Delta E)^3.$$

$E_0$  is synchronous energy of the beam and  $\eta$  is slip factor ( $=-0.0087$  for RR).  $\omega_0 = 2\pi f_0 = 2\pi/T_0$ . Where beam revolution period in RR  $T_0 \sim 11.12 \mu\text{sec}$ .  $\beta = v/c$ . The quantity  $\Delta E$  is energy spread of the beam. The remaining parameters are indicated in Fig.2.

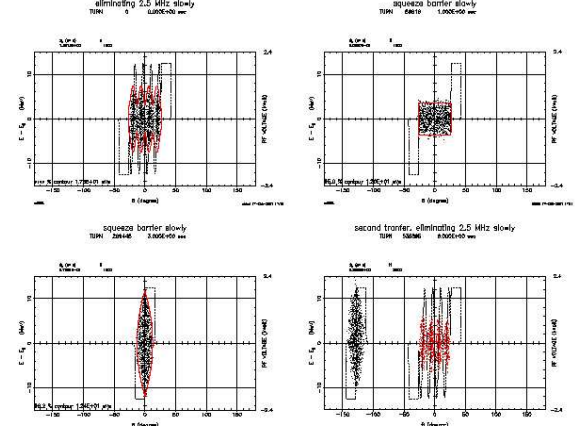
## PBAR STACKING IN BARRIER BUCKETS

RF manipulations involved in beam stacking in RR have been simulated using the program ESME[3]. These simulations do not take into account any rf noise or other instrumental effects which may give rise to additional longitudinal emittance growths. Therefore we demand all rf operations carried out in simulation to be fully adiabatic *i.e.*, with no emittance dilution. However, from practical point of view we allow up to about 5% longitudinal emittance dilution.

Figure 3 shows phase-space distributions of particles in  $(\Delta E, \Delta\phi)$ -space for four stages of beam stacking. The upper left figure shows beam in 2.5MHz rf bucket in RR. Next, the beam is debunched iso-adiabatically in about a second (see Fig.3 top right) in a barrier bucket with pulse width set to 491 nsec. This width was not fully optimized during the simulation. During the next two seconds the debunched beam particles are squeezed to match momentum spread of the stacked beam (notice that the shown here is a first transfer). There is a potential for emittance growth during squeezing and transferring the beam to stacked region. This emittance growth has to be minimized by optimizing speeds for squeezing and transferring the beam. The simulation showed that if beam squeezing is carried out faster than about 0.22 radian/sec in azimuthal plane we see emittance growth more than 5%. Some level of emittance growth may be acceptable for hot beam, but, not for cooled beam from AR. Fully squeezed beam is shown in bottom left side of Fig. 3. Finally, the new transfer along with the

previously transferred beam is shown in bottom right of Fig. 3.

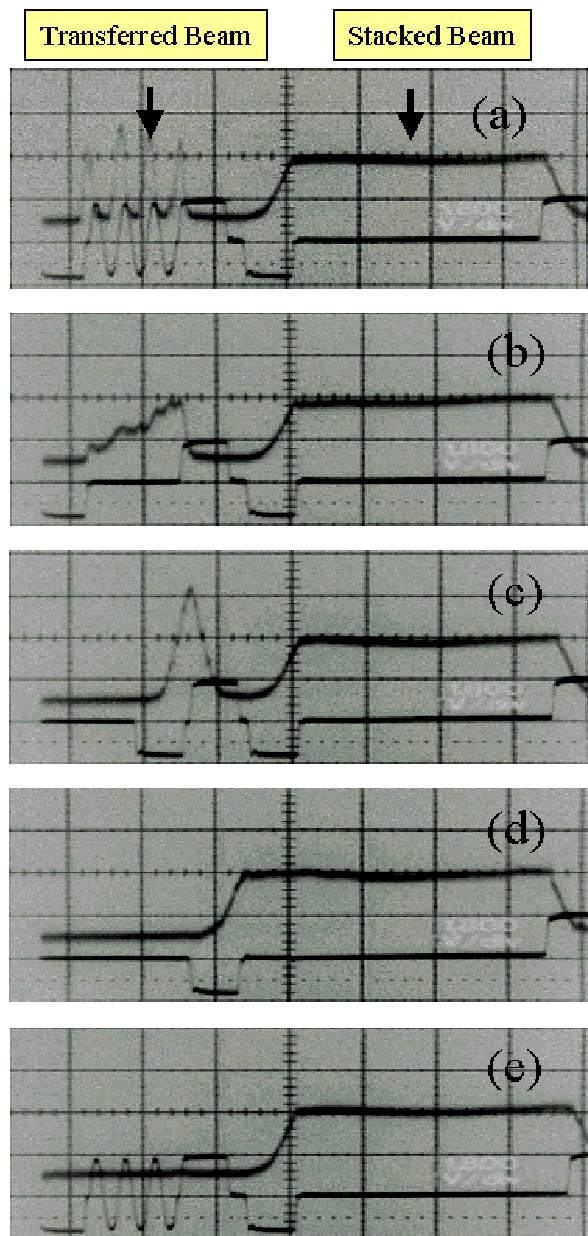
We have conducted series of experiments with protons and pbars in the RR barrier buckets to understand beam dynamics. We have used pbars from AR and protons from Booster.



**FIGURE 3.** Longitudinal beam dynamics simulation results for beam stacking. Shown are distribution of beam particles in  $(\Delta E, \Delta\phi)$ -space. The rf wave forms and buckets are also shown. For details see the text.

Experimental results for pbar beam stacking in RR are shown in Fig.4. The lower traces in each of the figures 4(a)-4(e) show RF cavity gap monitor voltage outputs. The upper traces are wall current monitor signals fed to a digital oscilloscope. The later results are similar to the projection of the phase space distributions shown in Fig.3 on  $\phi$  axis (*i.e.*, on horizontal axis). Descriptions of figures are as follows: a) four bunches on the left are newly transferred pbar beam and the long bunch on the right hand side is the stacked beam, b) beam immediately after debunching in barrier bucket. In this case, notice that the beam distribution is slanted indicating asymmetry in barrier pulse area. c) squeezed beam in barrier bucket, d) after transferring the newly stacked beam to originally stacked beam. e) rf waveform just before next beam transfer; this time notice the stacked bucket is slightly wider than in 4(a) to 4(d). So far, the maximum pbar stacked in RR was about  $30E9$  and that of proton beam was about  $750E9$  with a beam life time of a few hours.

We have carried out some preliminary experiments to un-stack the beam from a stacked beam and tried to transfer the beam to the MI. The sequences of this operation is essentially reverse of stacking.



**FIGURE 4.** Barrier buckets in RR (lower traces). Transferred and stacked pbars in RR (upper traces). (a) and (e) also show 2.5MHz rf wave inside transfer bucket.

Measurement of beam intensity and the longitudinal emittance of the beam in the barrier bucket is vital in understanding beam life time and emittance growth in RR. Presently, we are developing methods to measure beam intensity by using a technique very similar to fast bunch integrator[6]. Longitudinal emittance measurements in barrier

buckets is not trivial. We plan to measure it by use of schottky signals of the beam in the barrier buckets.

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